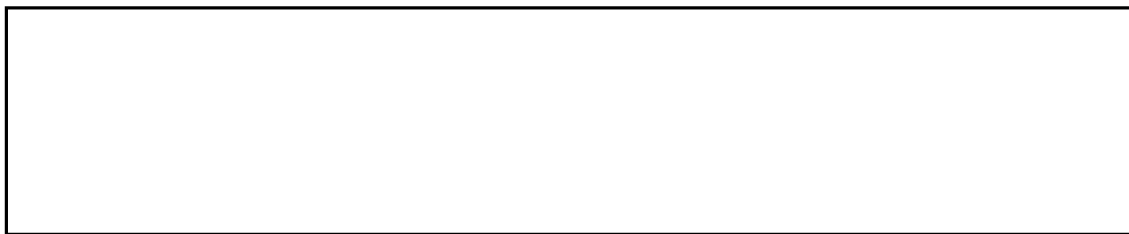
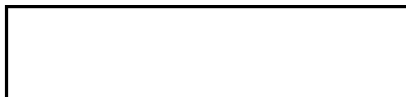


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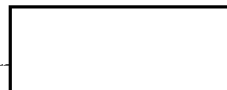


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PROPOSAL FOR PROTOTYPE COHERENT
LIGHT ENLARGER AND SPATIAL FILTER

DATE: April 24, 1963

PREPARED FOR: Internal Proposal



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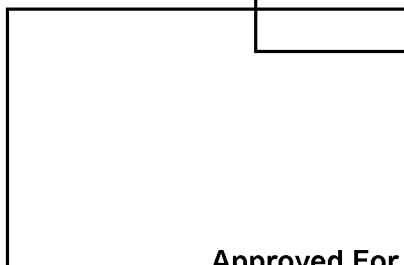


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SECTION I

INTRODUCTION

Aerial cameras are now being made which contain information at frequencies up to 200 cyc/mm. Other than microscopes, there are no known enlargers which have a high modulation transfer function at 200 cyc/mm, and microscopes have a miniscule field of view (e.g. 0.02 inches diameter for a suitable objective). Because there will be occasions when the modulation on the original negative is close to the eye's limit of detectability, it is desirable to have an enlarger with a modulation transfer function of 1.0 or, at least, very close to this. When the film's granularity imposes a higher detectability limit than the eye's limit — and this will frequently be the case with today's films — a modulation transfer function somewhat less than 1.0 is acceptable. However, when: (1) statistical variations of granularity produce a modulation detectability close to that of the eye, (2) grain integration techniques can be employed, and (3) allowance is made for tomorrow's improved films, then we believe it is worth striving for a modulation transfer function close to 1.0.

With this image forming requirement in mind, we have considered three other aspects of the problem:

(1) achieving the transfer function over a sizeable negative (2-1/4 inches by 2-1/4 inches being considered as a reasonable area)

(2) providing early delivery of the prototype

(3) designing a unit which will be compatible in speed and mode of operation with utilization as a production machine to enlarge entire rolls of negatives.

It is a pleasure to report that all of these objectives can be substantially achieved with the instrument described in this proposal. In Section II, the choice of coherent light is explained, which choice also permits us to propose the extremely valuable by-product of spatial filtering. In Section III, the proposed prototype and a breadboard instrument are described. The breadboard instrument will be used to shorten overall delivery time by allowing the very early choice of the best solution to each of the potential problems discussed in Section IV. Section V contains the proposed statement-of-work for a best effort program, and also includes a critical path method chart which substantiates the reasonableness of our proposed thirteen month delivery.

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SECTION II

CHOICE OF SYSTEM

A. LENS

We start with the requirement of producing a 4X enlarging system to expand a 2-1/4" x 2-1/4" object into a 9" x 9" image providing high information transmission at 200 cyc/mm. The 4X enlargement then contains information up to 50 cyc/mm, which can be adequately handled with existing equipment, and the 9" x 9" enlargement is of convenient size.

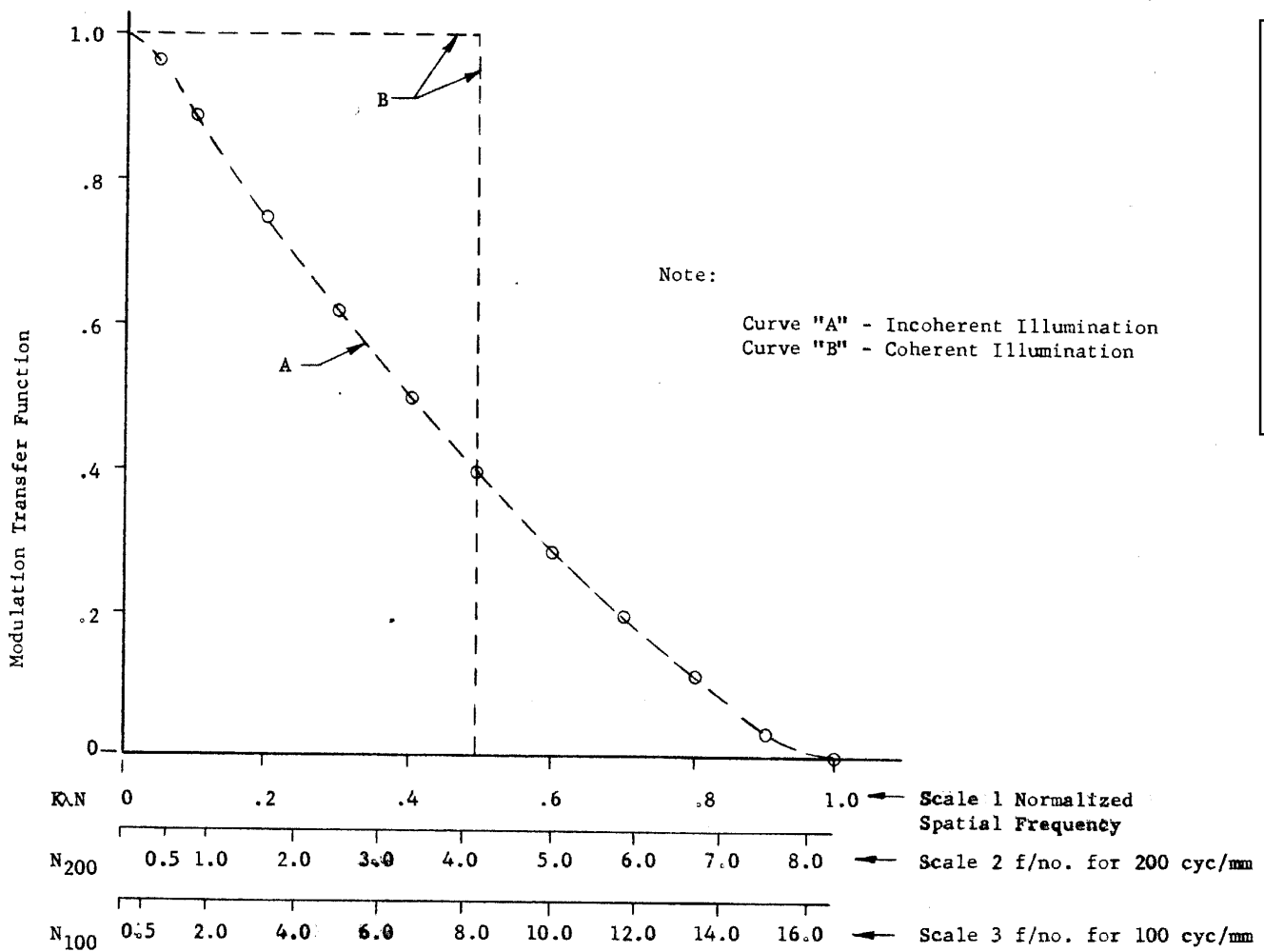
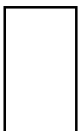
Approaching the problem in a conventional manner we can plot the modulation transfer characteristics of a diffraction-limited lens at 200 cyc/mm. as a function of the f/no. of the lens. The curve is identical to the normalized modulation curve of perfect lenses (with incoherent light), with a change in abscissa, as shown by curve A in Figure 2-1. For the diffraction-limited lens, the abscissa (Scale 1, Figure 2-1) is the normalized spatial frequency, KN , where K is the spatial frequency in cycles/millimeter, λ (6×10^{-4} mm) is the wavelength, and N is the f/no. of the imaging cone of light. For the modulation at 200 cyc/mm, the abscissa (Scale 2) becomes $KN\lambda = 200 \lambda N_{200}$, giving $N_{200} = \frac{KN\lambda}{200\lambda} = \frac{KN}{200}$; while at 100 cyc/mm the abscissa (Scale 3) is $KN\lambda = 100\lambda N_{100}$, giving $N_{100} = \frac{KN\lambda}{100\lambda} = \frac{KN}{100}$. From the curve, we can select the f/no. of the cone of light required to produce a required modulation at either 200 cyc/mm or 100 cyc/mm. Thus, if we select as a design objective a modulation

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of 0.9 at 200 lines/millimeter, we immediately see that our imaging cone of light must be faster than $f/1$. Since the lens is to be used at 4X magnification, the lens $f/\text{no.}$ must, therefore, be faster than 0.8. Without going into detail, it can be stated that such a lens would be practically impossible to design as a diffraction-limited system to cover the desired format.

Some minor improvement can be achieved by apodizing a relatively fast system to increase the modulation at low spatial frequencies at the expense of that at high spatial frequencies. The maximum increase in modulation is approximately 5% making this an unacceptable alternative.

A radical departure from conventional enlarging systems, through the use of coherent illumination, is found to yield great benefits in the modulation achievable with relatively slow lenses. The theoretically achievable modulation transfer function remains at unity out to one-half the limiting frequency for incoherent illumination, and then drops abruptly to zero. In Figure 2-1, Curve B shows that with coherent illumination an $f/4$ cone of light will yield 100% modulation transfer function at 200 cyc/mm. This becomes a reasonable lens to design and provides us with a basis for this proposal.

B. SPECIAL CONSIDERATIONS FOR COHERENT ILLUMINATION

The use of coherent illumination, and the discontinuous transfer characteristic it provides, presents us with some unusual properties that must be accommodated by our enlarging system. Of prime importance, since the original film platen must be coherently illuminated, is the fact that the optical path through all points of the format must be equal regardless of the variations in thickness of the emulsion and of the type of film backing. A wet gate is

therefore required, and the refractive index of the liquid must match that of the most non-uniform film component, i.e., the emulsion.

The lens elements will require careful fabrication since phase shifts across their apertures will result in longitudinal focal shifts as well as lateral displacements for different frequencies in the original. The tolerances, however, will be no tighter than that required for a high performance lens utilizing incoherent illumination. Since, on the basis of average aerial imagery, a modulation transfer function of 0.83 will reduce the limit only from 200 to 190 cyc/mm, this allowable drop from 1.0 can be distributed among fabrication tolerances.

This discontinuity in the transfer characteristic curve would introduce marked satellite images ("ringing") for high contrast targets showing sharp discontinuities (high frequency components). This is a very minor problem in the application proposed for this enlarger, since the original film will contain only low contrasts at high spatial frequencies.

C. LASER SOURCE

The requirement for coherent illumination naturally suggests the use of a laser source, because of its high degree of coherence. However, the transition of the characteristic curves from coherent to incoherent illumination is a uniformly varying function of the degree of coherence. Consideration must, therefore, be given to the possibility of using a monochromatic gas discharge source whose degree of coherence is appreciably less than a laser. It departs from the laser both in its spectral width and the energy available in a given angular subtense source used to illuminate the film.

If we attempt to enlarge a grating of 200 lines/millimeter and 60 millimeters width with a point source sufficiently monochromatic to maintain phase coherence, we require that $\Delta\lambda \ll \frac{\lambda}{n}$ where n is the total number of lines in the grating, for this variation admits up to a half-wave phase shift. Therefore,

$$\Delta\lambda \ll \frac{\lambda}{200 \times 60} = \frac{6000}{200 \times 60} \text{ \AA} = 0.5\text{\AA}$$

Since no readily available filter can produce passbands as narrow as this, it is not possible to utilize high-intensity, high-pressure gas discharges; and we must resort to the low pressure discharges with their lower intrinsic brightness.

We can apply a similar criterion to the limitation on angular subtense, $\Delta\theta$, of the source. This is: $\Delta\theta \ll \frac{\lambda}{W}$, where W is the width of the grating. Thus, $\Delta\theta \ll \frac{6 \times 10^{-4}}{60} = 10^{-5}$ radians. This is difficult to achieve, implying a 0.0005-inch diameter source (smallest practical size) at the focus of a 50-inch collimator. Next, $\Delta\Omega = \frac{\pi}{4} (\Delta\theta)^2$, where Ω is the solid angle of the source. If a low pressure mercury arc is operated at sufficiently low pressure and temperature to achieve the required 0.5\AA spectral line width, then the brightness of the green line is $B \cong 3 \times 10^{-4}$ watts/cm² steradian, and the illumination on the grating is $B\Delta\Omega \ll B \times \frac{\pi}{4} \times 10^{-10}$ watts/cm². The illumination of the enlarger platen, E , is 1/16 this value. Thus, $E \ll 1/16 B \times 7 \times 10^{-11}$ watts/cm² = $3/16 \times 10^4 \times 10^{-11} = 1.3 \times 10^{-15}$ watts/cm². Compared with this, a laser will radiate approximately 10^{-3} watts to cover, say, a 9 inch x 9 inch platen, i.e., $\frac{10^{-3}}{(2.54 \times 9)^2} = 2 \times 10^{-6}$ watts/cm².

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It is therefore seen that an exposure 10^{-9} the duration for a low-pressure Hg arc may be realized with a laser. This is a particularly important consideration in that very small vibration effects will markedly reduce the reproduction capabilities at the high frequencies. For a relatively fast emulsion, the exposure times for clear film become 10^{-3} seconds for the laser and $\gg 10^6$ seconds (twelve days!) for the Hg arc. This surprisingly large brightness ratio occurs because of the extremely small source size and spectral width required for coherence. With a microfilm-like film at the enlarger platen, and a 10% transmitting original, the laser exposure is about 0.5 seconds and that for the arc is unattainable. Even making a 100X more optimistic estimate of arc brightness that may be obtained without spectral broadening, a laser must still be chosen to keep reasonable exposure times when employing spatial filters. We are, therefore, preparing to obtain our coherent illumination for the enlarger with a He-Ne gas phase continuous laser operating at λ 6328.

SECTION III

DESCRIPTION OF SYSTEM

A. OPTICAL

The optical schematic for the proposed enlarger system is shown in Figure 3-1. It consists of a laser source, a source imaging lens and pinhole mask, a collimator lens, a wet gate for mounting the original film, lens 1 for forming the diffraction pattern produced by the film of the point source and collimating the light diffracted by the film, an available area in the spectrum plane (i.e., the image plane of the point source) for introducing spatial filtering, and lens 2 for imaging the original film on the enlarger platen. This schematic applies to both the breadboard and the prototype. The differences are tabulated in Table 3-1.

Lenses 1 and 2 are the collimator and camera lens for the enlarger and, therefore, have their focal lengths in the ratio of 1:4. Lens 1 has its exit pupil coincident with the spectrum plane. The focal length of the prototype has been selected to permit diffraction-limited performance over the 2-1/4" x 2-1/4" field, and the aperture provides collection of the first order diffracted rays for frequencies as high as 200 cyc/mm. The f/no., of course, is smaller than 4 to ensure the cut-off at a frequency above 200 cyc/mm. Since monochromatic radiation is employed, no chromatic correction is required and the elements can all be made from the same glass type. Lens 2 is a simple design problem because of its reduced speed. It requires an entrance pupil in the spectrum plane. Lens 2, like lens 1, can be made from a single glass type.

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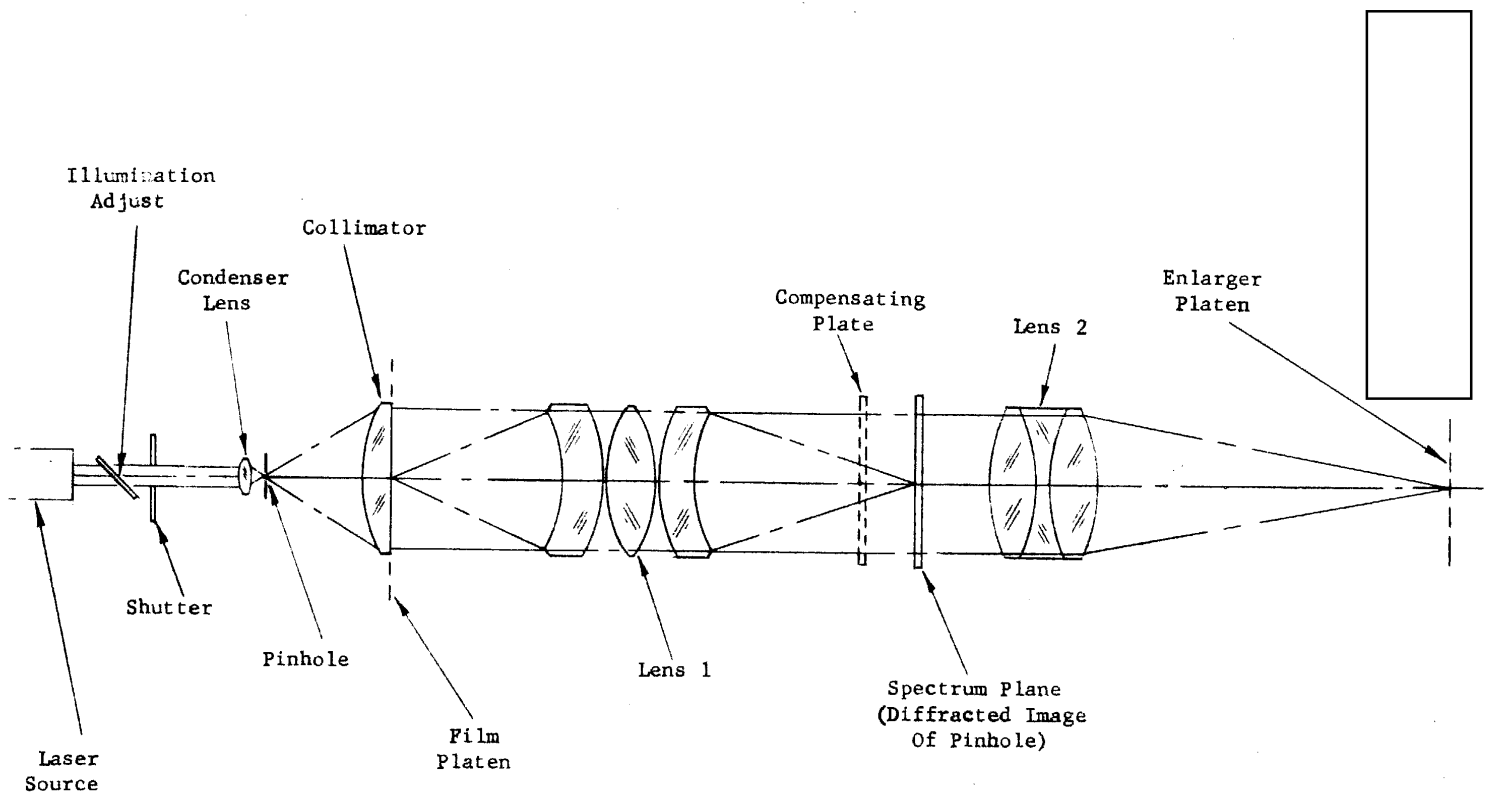


Figure 3-1. Optical Schematic

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TABLE 3-1

LEADING PARTICULARS OF PROPOSED BREADBOARD AND PROTOTYPE

	Breadboard	Prototype
Object Film	100 lines/millimeter 1 inch x 1 inch	200 lines/millimeter 2-1/4 inch x 2-1/4 inch
Magnification	~ 3.5:1	4:1
Lens No. 1	7.3° Total Field 100 lines/millimeter f/7.9 f.l. = 11.2 inches	14.4° Total Field ~200 lines/millimeter ~f/3.5 f.l. = 11.2 inches
Lens No. 2	40 inch T-5 (GFE) 30 lines/millimeter over 3.5-inch x 3.5-inch field	44.8 inch f/14 50 lines/millimeter over 9-inch x 9-inch field
Source	<div></div> Helium-Neon continuous wave laser	Same (The laser used on the breadboard will be incorporated in the de- liverable prototype).

In the case of the breadboard, the optics have been scaled down in cost and complexity by reducing the size and resolution requirements. The proposed breadboard will still permit study of all the coherence properties which can affect the prototype design.

B. MECHANICAL

A characteristic requirement of both breadboard and prototype enlarger equipments is mechanical stability such that the print film is exposed to a stationary image. The entire skeletal structure of the enlarger must be stiff, yet well damped, and isolated from externally induced stress and vibration.

The breadboard setup must be both simple and convenient for experimental work; furthermore, it will have completely served its purpose when the design decisions and measurements for the prototype have been made. Many of its parts will be used to complete the prototype. Thus, an appropriate frame design is considered to consist of a welded structural steel "bench" arranged for horizontal in-line layout of the optical path. It will be approximately 12 feet long, supported at three points, and damped by means of sandbag loading. Bolted to this unit structure will be the various optical subsystem mounts which, once aligned in accordance with system requirements, will retain permanent alignment integrity. The spectrum-plane plateholder assembly will be equipped with precision adjustments of the type available for microscope mechanical stages. The object film platen will provide for liquid immersion of one inch square film chips, in a "sandwich" between optically flat windows. The enlarger platen can be provided by the camera back of the aerial camera, which contains a vacuum-platen film advance and a magazine.

The prototype enlarger mechanical design will recognize requirements of convenience to the user, and thus will provide for viewing and selecting areas for enlargement from any 2-1/4-inch square portion of a roll of original film up to 9-1/2 inches wide. The optical path will be folded to the extent possible to provide reasonable cabinet dimensions. Since it is probably undesirable to fold the system beyond the liquid gate, the instrument will be quite high, perhaps ten feet overall.

The only operator controls which now seem required are source on-off, source attenuation and/or exposure time, two film advances, and perhaps focus, film, and spatial filter position adjustments.

C. SPATIAL FILTERING

Spatial filtering is a process by which the amount of energy contained in a particular frequency (or frequencies) of the original negative is reduced. This is accomplished by placing appropriate masks in the spectrum plane of the enlarger, since each frequency is brought to a focus at this plane. For example, if the negative to be enlarged is a square wave (Ronchi) grating of 10 lines/millimeter, then the spectrum will be a line of spots corresponding to 10, 30, 50, etc. lines/millimeter as well as a central zero-order spot corresponding to zero lines/millimeter, that is, the average transmittance. This central spot contains all the energy which is undiffracted by the negative (which is really acting like a diffraction grating); and, if this central spot is blocked by an opaque mask, then the enlarged image will not contain the zero-order energy, so all non-sharp edges will have increased sharpness. When a

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filter is used, the exposure time is obviously lengthened in proportion to the blocked energy. [] has restituted original images with image motion blur so that most of the blur losses are removed, and [] have enhanced the contrast of fine detail.¹

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Because the enlarger uses coherent light, the spectrum plane exists, and it can be used for filtering. Therefore, we plan to provide a simple mechanism for inserting spatial filters at this plane, and we will furnish a clear plate (no filter) and a zero-order filter with the instrument. The clear plate is required to maintain optical focus, when no filtering is desired. Other filters, to remove image motion or make an average correction for atmospheric seeing, are possible. However, we recommend deferring a contract for these until the prototype is delivered and in operation.

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SECTION IV

POTENTIAL PROBLEM AREAS

There are several potential problems in the development of the prototype. The breadboard will be used to investigate these in sufficient detail to select the best solution. In this section, the problems and some possible solutions are discussed.

Coherent light, which must be used for the illumination to obtain the desired modulation transfer function, is light in which the optical phase is everywhere equal across the transparency to be enlarged. By far the most difficult of the potential problems is maintaining this phase coherence. The core of this problem is almost certainly in the fact that the optical thickness of the film base and the emulsion is not everywhere uniform. The obvious solution is to mount the film in a fluid having an index of refraction equal to that of the emulsion, and to contain the fluid between two optical flats with about this same index of refraction. This leaves a residual problem which can only be investigated experimentally, which is perhaps the most compelling reason for the breadboard. The problem is that of determining how much variation in optical thickness of the film base can be compensated for with fluids. We have discovered that ester bases have some birefringence while acetate bases do not. Since the laser output is polarized, proper orientation of the laser's azimuth relative to film length may solve this problem, if it is, in fact, large enough to be troublesome.

Another, and related, problem is that of the fluid's uniformity of refractive index. There are numerous fluids which have the correct index, but the refractive index of all of these is somewhat temperature sensitive. Consequently, the tank may have to be thermally insulated.

Similarly, and still for reasons of phase coherence, the air in the instrument may prove to be too turbulent for satisfactory imagery. If so, either baffling or evacuating the upper part of the instrument should be a simple solution.

The laser source image at the pin hole is reimaged in the spectrum plane. This concentrated energy, about one milliwatt, could create air turbulence or could thermally distort the spatial filter. A microscope slide will be inserted near the source, and its transmission will be experimentally adjusted to reduce the energy, if required, to low enough levels.

Another potential problem is the scattering of light by sub-microscopic impurities and defects in the glass. If there is any evidence that this is a problem in the breadboard, the lenses for the prototype will be control ground, as there is some experimental evidence that controlled grinding reduces scattering.

A special problem of film handling results from the probable need for liquid immersion. Suitable liquids must be investigated, many of which are mixtures of volatile fluids. It is important that the liquid cell be designed to inhibit losses by evaporation in order to preserve the optical properties as well as to protect the operator from fumes and to prevent explosions. It is

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desirable that the liquid be sufficiently volatile so that rinsing or cleaning of film, after enlarging, will not be necessary. Many of these problems have been intensively investigated, and it is expected that satisfactory solutions will be found to provide the required performance with reasonable convenience.^{2,3,4}

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SECTION V

STATEMENT OF WORK

STAT ITEM 1 - [] will undertake on a best effort basis the engineering, design, and fabrication of the prototype Coherent Light Enlarger and Spatial Filter described in Section III. The design objective is a modulation transfer function of 0.83 at 200 cycles/millimeter. A nondeliverable breadboard will be assembled early in the program. The leading particulars of breadboard and prototype are summarized in Table 3-1. As part of this item, the contractor shall provide:

- (1) periodic informal progress reports
- (2) a reasonable amount of customer briefing material
- (3) a maintenance and instruction manual

Work will be on a CPFF basis. As an economy, it is further understood that all unexposed film required for breadboarding and test will be furnished by the customer; also, [] will refurbish a customer furnished 40-inch T-5 lens for use on the breadboard as lens No. 2.

STAT ITEM 2 - The source unit for breadboard and prototype will be one (1) [] Laser, to be provided on a straight fixed price basis.

STAT ITEM 3 - [] will provide the services of qualified engineers and technicians to assist the customer with the installation of the Coherent Light Enlarger and Spatial Filter at the customer's

facility and to demonstrate to the customer's personnel the operation of the instrument. This item will be on a Time and Material basis, estimated as one month elapsed time.

SCHEDULE

Figure 5-1 is the critical path method chart for the program. The scheduled delivery is 13 months.

The breadboard will be completed, and critical design problems evaluated before the major cost commitments must be made on the prototype. Therefore, a convenient time for a customer-contractor program review is 16 weeks after receipt of contract, when the breadboard has been properly evaluated.

The program shown in Figure 5-1 is about four months shorter than another program we considered, which is substantially identical except that no breadboard unit was included. The time saving is achieved by accomplishing all the design experimentation before major hardware commitments, and by determining the critical tests in parallel with prototype assembly rather than serially after prototype assembly. The actual proposal certainly contains less risk and is probably the least expensive program possible.

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